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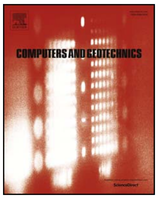

Research Paper

Classification and characteristics of soil arching structures in pile-supported embankments

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ABSTRACT

Soil arching effect is a key load-transfer component in pile-supported embankments. However, previous models that account for soil arching effect consider various assumptions and simplifications due to insufficient understanding of soil arching structures developed in pile-supported embankments. Consequently, the use of previous models in practice would potentially result in substantially different designs. This study aims to develop a reasonable classification system for the soil arching structures under different conditions, and to identify the characteristics and applicability of each structure. Firstly, a series of Discrete Element Method simulations were performed to investigate the evolution of soil arching structures under different conditions with emphasis on the embankment deformation behaviour. The simulation results show that soil arching structures under different conditions can be divided into three groups: (a) “shear plane arching”; (b) “partial arching”; and (c) “full arching”. This was followed by detailed analysis of the macro- and microscopic characteristics of each soil arching structure. Finally, the load-transfer mechanisms of the three soil arching structures are compared, and the influence of design parameters on the soil arching structure is discussed. It is concluded that contact force rotation induced by the pile-subsoil relative displacement causes the changes in load-transfer path, and thus the stress distribution is altered. However, the interaction and location of the rotated contact forces are considerably different under different conditions, which results in the development of various soil arching structures and significant differences in the deformation and the load-transfer mechanism of the pile-supported embankments. Two critical heights that govern the interaction and location of the rotated contact forces were identified: the critical arching height, h_{ca} (i.e., $0.8(s\text{-}a)$), and the critical overlying filling height, h_{co} (i.e., $3.0a$), where s is the pile spacing and a is the pile (or pile cap) width. It was shown that, for the design of the pile-supported embankments, both (s-a) and a should be considered.

1. Introduction

Pile-supported embankments have been extensively used in the construction of transportation infrastructure, including highways [1], high-speed railways [2] and bridge approach embankments [3], to overcome intolerable total or differential settlements, large lateral displacements and local instabilities typically associated with weak/soft subgrade soils [4,5]. The analysis performed by Arulrajah et al. [6,7] provided a detailed insight into the design and construction of the pile-supported embankments for high-speed railway projects. One of the key geotechnical design considerations is accounting for soil arching effect as a key load-transfer mechanism in pile-supported embankments.

A number of analytical models have been previously proposed for analysing the soil arching effect. These models consider various assumptions and simplifications. Theoretically, the existing soil arching models can be classified into the following three groups. The first group [8–13] considers the equilibrium of the soil mass based on the Marston theory [8] and Terzaghi theory [9]. The influence region of soil arching has a rectangular shape under 2-dimentional (2D) conditions or cylindrical shape under 3-dimentional (3D) conditions. The second group [14–21] is derived from the hemispherical soil arching model (i.e., the H&R model proposed by Hewlett and Randolph [14]). The load-transfer of soil arching is estimated using the limit equilibrium equations. All models in this group assume that the soil arching zone has a constant height that is equal to 0.5 times the pile clear spacing (i.e., $0.5(s\text{-}a)$, where s is the pile spacing and a is the pile (or pile cap) width) and that soil arching would reach the ultimate state at the arch crown or above the pile head. The third group [22–24] assumes a fixed boundary between the influence region and stable region. Embankment loads within the stable region are transferred to the piles directly, and load-transfer between the soil arching zone and the embankment fill below the arching zone was neglected.

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Some of the aforementioned soil arching models have been adopted by the relevant design codes and technical guidelines. For example, the Marston's theory [8] and the H&R model [14] were adopted by British Standard-BS8006 [25,26] for estimating the soil pressure acting on piles; the non-concentric hemispherical soil arching model proposed by Kempfert et al. [16] was utilised by German Standard-EBGEO [27]; the wedge-shape soil arching model developed by Carlson [23] was recommended in the Nordic Guidelines-NGG [28]; and the concentric arches model proposed by van Eekelen et al. [19,21] was considered in the Dutch Design Guideline-CUR 226 [29].

Nevertheless, it should be acknowledged that the assumptions and formulas used for the soil arching models adopted by the aforementioned design codes and technical guidelines are widely different. Further, several studies [30–35] have indicated that the results arising from those soil arching models are considerably different. There is no consensus among practitioners on the appropriate soil arching model to use for practical design [33,34,36]. The root cause of the significant differences between the existing models is the insufficient understanding of the virtual load bearing structure (termed as soil arching structure from this point onwards) developed in the pile-supported embankments.

The existing research mainly focuses on the soil arching effect developed in pile-supported embankments. However, it does sufficiently consider the soil arching structure along with the embankment deformation behaviour. For instance, Chen et al. [37] verified the existence of soil arching effect in pile-supported embankments and the effectiveness of this technique in reducing total and differential settlements based on three full-scale field tests. Moreover, field tests [38–40] have demonstrated that the insertion of geosynthetic reinforcement layer(s) between the embankment and piles can effectively improve the load-transfer efficiency and reduce the pile-subsoil relative displacement (Δs) of the pile-supported embankments. However, Lai et al. [41] numerically found that, for identical Δs, the geosynthetic reinforcement has negligible influence on the soil arching structure. Moreover, a large number of small-scale model tests, centrifuge tests, and numerical simulations have been performed to investigate the effects of various variables such as pile cap size [42,43], embankment height [44,45], pile clear spacing [46,47], fill properties [48,49], cushion thickness [46,50], and cyclic loading [51,52] on the soil arching effect and to understand the soil arching effect on the performance of pile-supported embankments.

With the recent increase in available computational power, the Discrete Element Method (DEM) has received increasing attention and popularity over the past few decades due to its ability to capture the flow characteristic of the granular fill on a fundamental level [41,42,48,53–56]. For instance, Jenck et al. [48] observed that the load-transfer behaviour of a pile-supported granular platform can be more accurately predicted by the DEM modelling compared to continuum modelling. Recent DEM studies highlighted important mechanisms that govern the performance on pile-supported embankments such as the "forming-failure-reforming" behaviour of the soil arching structure that develops as the surcharge increases [54] and the soil arching structure that evolves with the increase in Δs [41,55,56].

Recently, CT scanning [55,57] and particle image velocimetry (PIV) techniques [56,58] were also increasingly employed in small-scale model tests to visualise the embankment fill displacement, which can be used to identify the characteristics of the soil arching structure to some extent. As an outcome of these tests, various soil arching structures with different shapes have been proposed, such as arch-shaped [41,55], triangle-shaped [56,57] and tower-shaped [56]. Despite these important advancements in testing techniques, the macro- and microscopic characteristics of the soil arching structure, which are important for practical design considerations such as bearing and deformation behaviours, have not been fully understood.

It has been widely accepted that the soil arching structure contributes to the reduction of the local differential settlements of the pile-supported embankments. To avoid excessive local differential settlement, the design of the pile-supported embankments should account for the influence of the soil arching structure on the embankment deformation behaviour. Several previous studies recommended a critical embankment height (H_{crit}) to approximately account for this aspect of the soil arching structure. For instance, Demerdash [59] recommended that the embankment height (H) should be larger than 1.7 times of the pile clear spacing (s-a) to mitigate the differential settlement at the embankment surface (Δs_{es}). Jenck et al. [44] reported uniform settlement at the embankment surface for the laboratory model test with $H = 2.0(s\text{-}a)$. However, differential settlement was observed for the case with $H \approx 1.3(s\text{-}a)$. Chen et al. [60] proposed that differential settlement occurs at the embankment surface if $H < 1.4(s\text{-}a)$, whereas no differential settlement occurs when $H > 1.6(s\text{-}a)$. Moreover, Rui et al. [56,58] proposed that embankment surface differential settlement can be avoided for that case of $H/(s\text{-}a) > 1.75$ and $(s\text{-}a)/a \geq 2.5$. Consideration of $(s\text{-}a)/a$ in pile-supported embankments design would add another degree of complexity. The above shows that there is no consensus among previous studies regarding key design aspects. In light of this, further work is needed to provide insight for optimisation of relevant design methodologies.

Considering the above, DEM is used here to provide insight into the micromechanical behaviour of pile-supported embankments with particular emphasis on soil arching mechanisms. The main objective of this study is to investigate the soil arching structure in pile-supported embankments using the 2D DEM modelling software, Particle Flow Code in Two Dimensions (PFC^{2D}), version 3.1, developed by Itasca [61]. The study is divided into three parts: (1) classification of the soil arching structures mobilised under different conditions based on a series of DEM models; (2) detailed analysis of the characteristics of various soil arching structures; and (3) discussion of the load-transfer mechanisms and the effects of design parameters on soil arching structures.

2. DEM modelling and validation for reference cases

2.1. Problem description

Three reference cases covered in this study are summarised in Table 1. These cases are based on the 2D laboratory tests reported in Rui et al. [56]. Details about the laboratory test setup are shown in Fig. 1. The pile-subsoil relative displacement (Δs) was simulated by moving down a trapdoor-like steel plate through the lift. Yangtze River sand was used as the filling material for the construction of embankment, and the maximum test embankment height was 600 mm. Several miniature soil pressure cells, with 50 kPa measuring range and a measurement resolution of 0.03 kPa, were installed at the bottom of the

Table 1
Information about the reference cases selected in this study.

Case	*H* (mm)	*a* (mm)	(*s*-*a*) (mm)	*H*/(*s*-*a*)	*a*/(*s*-*a*)	Grain size (mm)	Remark
No. 1	150	300	300	0.5	1.0	1.4–2.0	Test No. 4 in Rui et al. [56]
No. 2	150	75	75	2.0	1.0	0.25–0.425	Test No. 1 in Rui et al. [56]
No. 3	600	75	300	2.0	0.25	1.0–1.4	Test No. 16 in Rui et al. [56]

Note: *H*-embankment height; *s*-pile (or pile cap) spacing; *a*-pile (or pile cap) width.